PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G02B 27/46

A1

(11) International Publication Number: WO 97/41478

(43) International Publication Date: 6 November 1997 (06.11.97)

(21) International Application Number: PCT/IL97/00136

(22) International Filing Date: 29 April 1997 (29.04.97)

(30) Priority Data:
118057 29 April 1996 (29.04.96) IL

(71) Applicant *(for all designated States except US)*: JC TECHNOLOGIES LTD. [IL/IL]; 21 Havaad Haleumi Street, 93721 Jerusalem (IL).

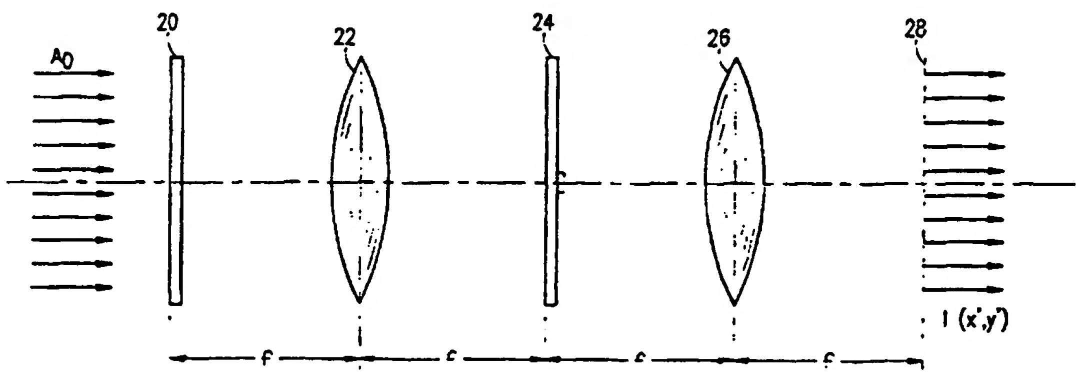
(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: EISENBERG, Naftali, Paul [IL/IL]; 47 Harav Uziel Street, 96423 Jerusalem (IL). ARIELI, Yoel [IL/IL]; 14 Rabbi Meir Street, 93185 Jerusalem (IL).

(74) Agents: SANFORD, T., Colb et al.; Sanford T. Colb & Co., P.O. Box 2273, 76122 Rehovot (IL).

(81) Designated States: AL, AM, AT, AT (Utility model), AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, CZ (Utility model), DE, DE (Utility model), DK, DK (Utility model), EE, EE (Utility model), ES, FI, FI (Utility model), GB, GE, GH, HU, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SK (Utility model), TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: OPTICAL PHASE ELEMENT



(57) Abstract

A method for modulating a beam of radiation to project a desired intensity distribution through an optical phase element (20), including selectively shifting the phase of the beam as a function of lateral position, based on the desired intensity distribution; filtering the phase-shifted beam through a Fourier filter (24) according to spatial frequencies thereof, and focusing the filtered beam with an imaging lens (26). A desired phase shift is determined at a plurality of lateral positions in the beam, as a function of the desired intensity at respective, corresponding points in an image plane (28) of the beam.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece			TR	Turkey
BG	Bulgaria	HU	Hungary	ML	Mali	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MN	Mongolia	UA	Ukraine
BR	Brazil	IL	Israel	MR	Mauritania	UG	Uganda
BY	Belarus	IS	Iceland	MW	Malawi	US	United States of America
CA	Canada	IT	Italy	MX	Mexico	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NE	Niger	VN	Viet Nam
CG	Congo	KE	Kenya	NL	Netherlands	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NO	Norway	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	NZ	New Zealand		
CM	Cameroon			PL	Poland		
CN	China	KR	Republic of Korea	PT	Portugal		
CU	Cuba	KZ	Kazakstan	RO	Romania		
CZ	Czech Republic	LC	Saint Lucia	RU	Russian Federation		
DE	Germany	LI	Liechtenstein	SD	Sudan		
DK	Denmark	LK	Sri Lanka	SE	Sweden		
EE	Estonia	LR	Liberia	SG	Singapore		

OPTICAL PHASE ELEMENT

FIELD OF THE INVENTION

The present invention relates generally to optical components and systems, and specifically to computer-generated optical phase elements.

BACKGROUND OF THE INVENTION

Phase objects and phase contrast methods of optical imaging are well known in the art, as described, for example, by Max Born and Emil Wolf in Principles of Optics, Fourth Edition (1970), pages 424-428, which is incorporated herein by reference.

The best-known and most powerful phase contrast method was described by Zernike in 1935 and is commonly used in biological microscopy and in other fields. Zernike's method allows for observation of a transparent phase object, i.e., an object having internal structure that induces a laterally-varying phase shift in light that is transmitted through it, but does not cause variations in the intensity of the transmitted light. In order to observe the phase shift, the object is illuminated with coherent light, and the transmitted light is focused by an objective lens. A phase plate is introduced at the focal plane of the objective. This phase plate typically includes a small central zone, which optically retards or advances the phase of light transmitted through the zone, relative to the remainder of the field. A second lens collects the light from the phase plate and focuses it onto an image plane. The resultant intensity distribution at the image plane is functionally dependent at every point on the phase change due to a corresponding point in the object.

Optical phase elements, which alter the phase of incident light without substantially affecting its intensity distribution, are known in the art, including for example, diffraction gratings, phase holograms and other diffractive optical elements (DOE's). Optical phase elements are designed, generally by computer, to provide desired spectrum and intensity shaping of an incident light beam. The most popular method for designing optical phase elements is an iterative method based on the Saxton and Gerchberg algorithm, as described, for example, by R.W. Gerchberg and W.O. Saxton in Optik 35 (1972), pages 237-246. This iterative method is time consuming, however, and is impractical for real-time computer generation of DOE's.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide phase elements, for use in accordance with the phase contrast method.

In one aspect of the present invention, optical phase elements are used in accordance with the phase contrast method to shape a beam of coherent light.

In another aspect of the present invention, optical phase elements are used to modulate a beam of light, so as to project a video image.

It is a further object of the present invention to provide apparatus for projecting images, comprising an optical phase element, and using the phase contrast method.

It is yet another object of the present invention to provide methods for generating phase elements and modulating radiation beams.

In preferred embodiments of the present invention, an optical phase element is designed so as to produce a desired phase profile in a transmitted light beam, wherein the desired phase profile is derived, in accordance with a method hereinafter described, from a desired intensity profile. A beam of light, which is preferably spatially coherent, is incident on and transmitted through the optical phase element, and is then focused by an objective lens onto a Fourier filter. The Fourier filter shifts the phase of light rays that pass through a central zone in the filter, concentric with the optical axis, relative to rays in the remainder of the optical field. An imaging lens focuses the light from the Fourier filter onto an image plane, where the desired intensity profile is obtained.

In some preferred embodiments of the present invention, the optical phase element is a diffractive optical element. Preferably this element is generated by computer calculation and fabricated by a multistep lithographic process.

In one preferred embodiment of the present invention, the beam of light incident on the optical phase element is a substantially uniform plane wave. The optical phase element is designed and constructed so that the transmitted beam at the image plane has a desired intensity profile, for example, a substantially Gaussian beam profile.

It will be understood, however, that the principles of the present invention may similarly be applied to design and construct optical phase elements that produce desired phase profiles in transmitted beams when non-uniform and/or non-plane waves are incident thereon, so as to produce desired intensity profiles in image planes thereof.

In other preferred embodiments of the present invention, the optical phase element is a reflective element, which produces desired phase shifts in a reflected beam of light. The beam reflected from the optical phase element is then focused by an objective lens onto a Fourier filter, and then focused by an imaging lens, substantially as described above in regard to transmissive optical phase elements. Although preferred embodiments

are largely described herein with reference to transmissive optical elements, it will be appreciated that similar preferred embodiments of the present invention may generally be constructed utilizing reflective optical phase elements and/or reflective Fourier filters, as well as curved mirrors in place of one or more lenses.

In still other preferred embodiments of the present invention, the optical phase element is an addressable array of phase-shifting elements, such as a liquid crystal array or other spatial light modulator. The elements are electronically addressable so as to create a desired phase modulation of a beam transmitted therethrough. The transmitted beam is focused by an objective lens onto a Fourier filter, which shifts the phase of light rays that pass through a central zone in the filter, as described above. An imaging lens focuses the light from the Fourier filter onto an image plane, where the desired intensity profile is obtained.

In some such preferred embodiments of the present invention, the transmitted beam is modulated by the array so as to project a video image. Preferably the array is addressed by a computer so as to project, after filtering, moving video images, preferably in real time. Preferably the imaging lens projects the video images onto a screen at the image plane. The light that is incident on and transmitted by the apparatus is preferably spatially coherent, and may be monochromatic or polychromatic. It will be appreciated that the array transmits substantially all the light that is incident on the array, thereby allowing for a brighter transmitted image, with less undesirable heating of the array, than in video image projectors known in the art.

In further preferred embodiments of the present invention, apparatus for projecting video images comprises three addressable arrays of phase-shifting elements, along with one or more objective lenses, one or more Fourier filters, one or more imaging lenses and a screen, as described above. Each of the arrays transmits a beam of light of a respective different color, preferably the colors red, green and blue. The apparatus thus projects three images, each of a different color, which are combined at the screen to present a single polychromatic image to viewers.

In further preferred embodiments of the present invention, a method for generating an optical phase element, so as to give a desired intensity distribution in an image plane, comprises determining the phase shift desired at each point in the optical phase element as a function of the desired intensity at a corresponding point in the image plane. The element is then fabricated, using methods known in the art, so as to impart the desired phase shift on a beam of light that is incident thereon. The optical phase element thus generated is used in conjunction with a Fourier filter, as described above, to create the desired intensity distribution in a beam of transmitted light.

Preferably the phase shift at each point in the optical phase element is given by an inverse trigonometric function, preferably an inverse sine function, wherein the argument of the function includes the desired intensity at the corresponding image plane point.

In some preferred embodiments of the present invention, generating the optical phase element also includes etching a transparent substrate so as to give the desired phase shift at each point thereof.

In other preferred embodiments of the present invention, generating the optical phase element includes electronically driving an addressable array of phase-shifting elements, so as to give the desired phase shift at each element thereof.

In some preferred embodiments of the present invention, the addressable array is driven in real time, and is used in projecting a real-time video image.

It will be appreciated that although the above preferred embodiments have been described with reference to optical systems, the inventive principles of the present invention may similarly be applied to generate desired intensity distributions in beams of other types of radiation, for example, microwave or ultrasound radiation.

There is therefore provided, in accordance with a preferred embodiment of the present invention, a method for modulating a beam of radiation to project a desired intensity distribution, including the steps of selectively shifting the phase of the beam as a function of lateral position, based on the desired intensity distribution; filtering the phase-shifted beam according to spatial frequencies thereof; and focusing the filtered beam.

Preferably, selectively shifting the phase of the beam includes determining a desired phase shift at a plurality of lateral positions in the beam, as a function of the desired intensity at respective, corresponding points in an image plane of the beam.

Preferably, selectively shifting the phase of the beam also includes generating driver signals, for driving an addressable array of phase-shifting elements to produce phase shifts in the beam. Preferably, the phase shifts of the phase-shifting elements are changed repeatedly, so as to project video images.

Preferably, filtering the beam includes focusing the beam and shifting the phase of radiation in a central zone of the focused beam, relative to the remaining portion of the beam, preferably by a phase shift generally equal to $\pi/3$ radians.

There is further provided, in accordance with a preferred embodiment of the present invention, a method for producing a phase element, for generating a desired intensity distribution, including the steps of determining a desired phase shift at a plurality of points in the phase element, as a function of the desired intensity at respective, corresponding points in an image plane; and producing the desired phase shift at each of the plurality of positions.

Preferably, producing the desired phase shift includes performing a multistep lithographic process.

Preferably, determining a desired phase shift includes calculating a trigonometric function of the desired intensity, more preferably an inverse sine function, and most preferably by an inverse sine function generally given by

$$\phi(x,y) = \sin^{-1}\left\{\frac{I(x',y')}{2|C|^2} - 1\right\}$$

wherein $\phi(x,y)$ is the desired phase shift, $I(x',y')$ is the desired intensity distribution, and C is a constant.

There is also provided, in accordance with a preferred embodiment of the present invention, apparatus for generating an intensity distribution in a beam of light, including at least one optical phase element, on which a beam of light is incident, the element inducing laterally-varying phase shifts in the beam of light; a Fourier filter, which receives light from the optical phase element and filters the light as a function of spatial frequency; and an imaging lens, which receives light from the filter and focuses the light, wherein the phase shift induced by each point in the optical phase element is determined by a desired intensity at a corresponding point in an image plane.

Preferably, the optical phase element is a transmissive element, which is preferably substantially transparent.

Alternatively, the optical phase element is a reflective element.

Preferably the apparatus includes an objective lens, which focuses light from the optical phase element onto the Fourier filter.

Preferably, the Fourier filter includes a central zone, which shifts the phase of light incident thereon relative to the phase of light incident on other zones thereof, and a peripheral zone, which shifts the phase of light incident thereon by a constant phase shift, the peripheral zone comprising substantially all the area of the filter outside the central zone. Preferably the Fourier filter shifts the phase of light incident thereon generally in accordance with a phase shift function given by:

$$H(\xi,\eta) = \begin{cases} a \cdot \exp(i\alpha) & \xi = \eta = 0 \\ 1 & elsewhere \end{cases}$$

wherein $H(\xi,\eta)$ is the phase shift, ξ and η are lateral position coordinates, and a and α are constants.

Alternatively, the condition $H(\xi,\eta)=a\cdot\exp(i\alpha)$ applies throughout the central zone of the filter.

Preferably, the optical phase element includes a diffractive optical element.

Alternatively, the optical phase element comprises an addressable array of selectively-variable phase-shifting elements. Preferably, the addressable array is a liquid crystal matrix array.

Preferably, the apparatus includes a mosaic color filter, which is preferably adjacent to the addressable array.

Alternatively, the at least one optical phase element includes three optical phase elements, arranged so that a beam of light of a different, respective color is incident on each of the optical phase elements, and the beams from the three optical phase elements are combined to form a color image.

Preferably, the apparatus is characterized by an optical magnification, the beam of light incident on the at least one optical phase element has substantially uniform intensity, and the product of the intensity of light at a point in the image plane and the optical magnification is substantially greater than the intensity of the incident beam of light.

The present invention will be more fully understood from the following detailed description of the preferred embodiments thereof, taken together with the drawings in which:

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic illustration of optical apparatus, in accordance with a preferred embodiment of the present invention;

Fig. 2 is a schematic illustration of optical apparatus, in accordance with another preferred embodiment of the present invention;

Fig. 3A is an isometric representation of the phase function of an optical phase element, in accordance with a preferred embodiment of the present invention;

Fig. 3B is a schematic, sectional representation of an optical phase element, whose phase function is shown in Fig. 3A;

Fig. 4 is a schematic illustration of optical projection apparatus in accordance with a preferred embodiment of the present invention;

Fig. 5 is a schematic illustration of a mosaic color filter, for use in conjunction with the apparatus of Fig. 4 in a preferred embodiment of the present invention; and

Fig. 6 is a schematic illustration of optical projection apparatus in accordance with another preferred embodiment of the present invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Reference is now made to Fig. 1, which illustrates optical apparatus in accordance with a preferred embodiment of the present invention. A coherent plane wave is perpendicularly incident from the left on a transparent optical phase element 20. Element 20 is preferably characterized by the complex transmittance function:

$$\tau(x,y) = c \cdot \exp[i\phi(x,y)] \tag{1}$$

where c is a complex constant and $\phi(x,y)$ is the variable phase shift, induced in the transmitted beam, as a function of lateral position (x,y). Preferably $|c|$ is substantially equal to one, although $|c|$ may be less than one if element 20 attenuates light that it transmits. Taking the amplitude of the incident plane wave to be a complex constant, A_o, the amplitude of the beam transmitted by element 20 is then:

$$u(x,y) = C \cdot \exp[i\phi(x,y)] \tag{2}$$

where $C = A_o c$. It will be observed that the structure of optical phase element 20 is normally invisible and not seen in the transmitted beam, since the intensity of the beam, $|C|^2$, is a constant over the entire beam.

As shown in Fig. 1, objective lens 22 focuses the beam transmitted by optical phase element 20 onto Fourier filter 24. Filter 24 is preferably a phase plate of a type known in the art, for example a Zernike phase plate, which retards or advances the phase of waves in the transmitted beam having spatial frequency substantially equal to zero, relative to waves having other spatial frequencies. Such a phase plate is preferably characterized closely by the transmittance function:

$$H(\xi,\eta) = \begin{cases} a \cdot \exp(i\alpha) & \xi = \eta = 0 \\ 1 & \mathit{elsewhere} \end{cases} \tag{3}$$

ξ and η are the lateral coordinates in the Fourier plane, i.e., at filter 24, a is the transmittance of the central region of the filter and α is the phase shift induced thereat. It is understood in reference to equation (3), that, as is known in the art, the central zone of filter 24 extends slightly beyond the central point where $\xi=\eta=0$, due to constraints of optical fabrication and the finite size of the optical aperture. Outside this extended

central zone the phase shift induced by filter 24 is substantially constant over the entire area of the filter.

The beam transmitted through filter 24 is given by the product $H(\xi,\eta)\cdot Y(\xi,\eta)$, where $Y(\xi,\eta)$ is the Fourier transform of the beam amplitude u(x,y). This transmitted beam is focused by imaging lens 26 onto image plane 28, where the intensity at any point (x',y') is substantially given by:

$$I(x',y') = |C|^2 |a\cdot\exp(i\alpha) + u(x,y) - 1|^2 \qquad (4)$$

The intensity I(x',y') is given exactly by equation (4) for an ideal phase plate exactly in accordance with equation (3).

Substituting the functional form of u(x,y) from equation (2), and rearranging terms in equation (4), we obtain:

$$I(x',y') = |C|^2 \left\{a^2 + 2\left[1 - a\cdot\cos\alpha - \cos\phi(x,y) + a\cdot\cos(\alpha - \phi(x,y))\right]\right\} \qquad (5)$$

Assuming that filter 24 retards light incident at $\xi=\eta=0$ by $\alpha=\pi/3$, without affecting its amplitude, i.e., a=1, equation (5) reduces to:

$$I(x',y') = 2|C|^2 \left\{1 + \sin\left(\phi(x,y) - \frac{\pi}{6}\right)\right\} \qquad (6)$$

For convenience, a normalized intensity, I'(x',y'), independent of the uniform input beam amplitude and the uniform transmittance of filter 24, may be defined as:

$$I'(x',y') = \frac{I(x',y')}{2|C|^2} = 1 + \sin\left(\phi(x,y) - \frac{\pi}{6}\right) \qquad (7)$$

It will be understood, however, that in other preferred embodiments of the present invention, as will be described below, other values of a and α may be chosen, based on theoretical and/or empirical considerations relating specifically to such embodiments. In such embodiments, I(x',y') will be given by other equations, generally similar in form to equation (6), but including different constant terms, dependent on the values of a and α.

Referring to equation (6), it will be observed that the non-uniform intensity of the transmitted beam, at any point in image plane 28, $I(x',y')$, is a function of the sine of phase shift $\phi(x,y)$ at a corresponding point in phase element 20. It will be appreciated that if the intensity transmittance of phase element 20, which is given by $|c|^2$, is substantially equal to one, then $I(x',y')$ will generally vary between zero and $4|A_0|^2$. Hence, the intensity at a point in the image plane can be up to four times the substantially uniform intensity of the incident beam, assuming 1:1 magnification and subject to the constraint that over the entire beam, energy must be conserved. In systems based on conventional intensity-modulating optical elements, as is well-known in the art, the transmitted intensity under such conditions will not exceed $|A_0|^2$ at any point.

Fig. 2 shows an alternative preferred embodiment of the present invention, in which optical phase element 30 is a reflective element, which induces desired phase shifts in light that is incident thereon. It will be appreciated that the principles explained above may equally be applied to reflective elements of this type. The beam reflected from element 30 is reflected by a plane reflector 32, oriented substantially perpendicularly to element 30, so as to equalize the optical path lengths of parallel rays of light at different lateral displacements from optical axis 31. The beam is then focused by an objective lens 33 onto a Fourier filter 34, and the filtered beam is then focused by an imaging lens 35, substantially as described above in regard to Fig. 1. An intensity distribution substantially as defined by equation (6) is obtained at an image plane 36.

Thus, although preferred embodiments of the present invention are largely described herein with reference to transmissive optical phase elements, it will be appreciated that similar preferred embodiments may generally be described with reference to reflective optical phase elements. Furthermore, alternative embodiments of the present invention may be produced using only reflective elements, as are known in the art, for example by substituting a reflective phase-shifting filter for Fourier filter 34, and mirrors, such as off-axis paraboloidal mirrors, for lenses 33 and 35.

Returning to the preferred embodiment of the present invention shown in Fig. 1, lenses 22 and 26, are shown as biconvex lenses, having equal focal lengths. Optical phase element 20 is positioned substantially at the front focus of lens 22, and Fourier filter 24 is positioned substantially at the back focus of this lens. Similarly, lens 26 is so positioned that Fourier filter 24 is substantially at the front focus of lens 26. Thus, the magnification of element 20 onto image plane 28 at the back focus of lens 26 is substantially equal to one. It will be appreciated, however, that in other preferred embodiments of the present invention, other types and combinations of lenses, as are known in the art, may be used, and different magnifications may equally be chosen. Fig.

4, for example, schematically shows a system having a greater magnification than that shown in Fig. 1.

In preferred embodiments of the present invention, in order to generate a desired image intensity pattern I(x',y'), the required phase shift profile of element 20, $\phi(x,y)$, is determined by inverting equation (7), assuming that a coherent plane wave is incident thereon:

$$\phi(x,y) = \sin^{-1}\{I'(x',y') - 1\} + \frac{\pi}{6} \tag{8}$$

Because of the simple, analytical form of equation (8), it will be appreciated that the method described here can be used to generate optical phase elements quickly and conveniently, even in real time at video rates, using an ordinary, inexpensive computer.

Fig. 3A shows an optical phase function 38, as a function of lateral position (x,y), and Fig. 3B shows a corresponding fixed-phase optical phase element 37, useful, for example, in beam shaping applications, in accordance with a preferred embodiment of the present invention. It will be appreciated that the phase shift induced in a beam incident on element 37 varies laterally due to the varying thickness of the element. Element 37 may be introduced in the position of element 20, as shown in Fig. 1, in order to convert an incident plane wave into a symmetrical, substantially Gaussian beam at image plane 28, i.e.:

$$I(x',y') = k_0 \cdot \exp\left[-\frac{(x')^2 + (y')^2}{r_0^2}\right] = k_0 \cdot \exp\left[-\frac{(r')^2}{r_0^2}\right] \tag{9}$$

where k_0 and r_0 are constants, and $r' = \sqrt{(x')^2 + (y')^2}$. The constant phase shift $\pi/6$ in equation (8) may be ignored, since it has no impact on the intensity distribution at image plane 28.

Empirically it has been observed that the beam generated by the system of Fig. 1, incorporating element 37 as described here, deviates slightly from the desired Gaussian shape.. This deviation is due primarily to the fact that equation (4) expresses an approximate relation, and does not take into account the finite size of the central, phase-shifting zone in Fourier filter 24. Edge effects at the border between the central zone and the peripheral area of the filter may also need to be taken into account. It has been found empirically that the beam at image plane 28 can be made to fit the desired profile

more closely by choosing a different value for the phase retardation α of the central zone and then deriving suitable constant factors for correction of equation (8), for example by using Fast Fourier Transform (FFT) analysis of the optical system and linear or non-linear fitting techniques known in the art.

Although for the sake of simplicity in describing the principles of the present invention, equation (8) above has been derived with reference to incidence of a uniform plane wave on element 20, in other preferred embodiments of the present invention, an incident beam of radiation may have non-uniform intensity and/or comprise non-plane waves. In such embodiments, the amplitude of radiation incident on an optical phase element is generally given by a complex function A(x,y), so that in place of equation (2) above, the amplitude of the beam transmitted by the phase element is given by:

$$u(x,y) = cA(x,y)\cdot \exp[i\phi(x,y)] \qquad (10)$$

As described above, the Fourier transform of u(x,y), $Y(\xi,\eta)$, is multiplied by the filter function $H(\xi,\eta)$, given by equation (3). The product $H(\xi,\eta)\cdot Y(\xi,\eta)$ is reverse-transformed to derive the intensity I(x',y') of a transmitted beam in an image plane thereof:

$$I(x',y') = c^2 \left| A(x',y')\exp[i\phi(x',y')] + [\exp(i\alpha)-1]\int_{-\infty}^{\infty} A(x,y)\exp[i\phi(x,y)]dxdy \right|^2 \qquad (11)$$

Although the resultant intensity is functionally more complex than that given by equation (4) for the uniform plane wave case, I(x',y') may still be found analytically at every point in the image plane. Inversely, known functional forms of I(x',y') and A(x,y) may generally be used to determine a phase function $\phi(x,y)$ and, thus, to design suitable optical phase elements, in accordance with the principles of the present invention, such that when a beam characterized by amplitude A(x,y) is incident on such an element, the transmitted beam in the image plane will have intensity distribution substantially given by I(x',y').

The phase function $\phi(x,y)$ is preferably determined analytically from equation (11). To do so, we first note that since the function A(x,y) is finite, the integral in the equation may be generally expressed as:

$$\int_{-\infty}^{\infty} A(x,y)\exp[i\phi(x,y)]dxdy = \Gamma + i\Delta \tag{12}$$

where Γ and Δ are real, finite constants.

Based on the known functional form of A(x,y), φ(x,y) may generally be chosen so that Δ=0. For example, if A(x,y) is symmetrical about the X-axis, so that A(x,y)=A(-x,y), then by setting φ(x,y)=-φ(-x,y), we will obtain the desired condition of Δ=0. If we also set α=π, then equation (11) reduces to:

$$I(x',y') = c^2 \left| A(x',y')\exp[i\phi(x',y')] - 2\Gamma \right|^2 \tag{13}$$

Equation (13) may now be solved for φ to give:

$$\phi(x,y) = -i\log\left\{\frac{\sqrt{I(x,y)}\cdot\exp[i\psi(x,y)] + 2\Gamma}{cA(x,y)}\right\} \tag{14}$$

where ψ(x,y) is an arbitrary phase distribution, which is preferably chosen so as to give a desired functional form of φ, for example φ(x,y) real and φ(x,y)=-φ(-x,y).

In preferred embodiments of the present invention, phase profiles calculated in accordance with equation (8), or alternatively, in accordance with empirically modified versions of this equation or other formulations derived generally from equation (11) or (14), are used to fabricate optical phase elements. These elements operate in conjunction with apparatus such as that shown in Fig. 1 to convert incident beams of spatially-coherent radiation to transmitted beams having any desired intensity profile I(x',y'). In one such preferred embodiment, a diffractive optical element (DOE) is fabricated in a multi-step lithographic process, as is known in the art, so as to have a phase-retardation profile step-wise approximating that given by equation (9). It will be appreciated, however, that the variation of intensity in the image plane will then likewise be in steps, the profile of the steps approximating the desired smooth intensity profile.

Fig. 4 shows another preferred embodiment of the present invention, in which video projection apparatus 39 includes an addressable phase-shifting element array 40, which serves as an optical phase element. A coherent, collimated, monochromatic beam of light is normally incident on array 40, which is preferably a liquid crystal matrix array

or other type of spatial light modulator known in the art for spatial modulation of a transmitted beam, for example spatial light modulator model DR0256B, manufactured by Displaytech, Inc., of Boulder, Colorado, U.S.A. Array 40 modifies the phase of light that it transmits, but without modulating the intensity thereof.

Processor 42 receives video data and uses these data to determine the desired phase shift at each element in array 40, preferably substantially in accordance with equation (8), or an empirically modified version of this equation, and to drive the array accordingly. Preferably the calculation is performed by a computer in real time and updated at video rate (for example, 30 times per second), and is used to create a real-time video image in the transmitted beam.

Objective lens 44 focuses the beam transmitted through array 40 onto Fourier filter 46, as described in reference to Fig. 1. Projection lens 48 then focuses the light transmitted by the Fourier filter onto screen 50, so as to create a video image in accordance with the video data input to processor 42. It will be appreciated that because the array 40 transmits substantially all the light that is incident on the array, the transmitted image is brighter (as was discussed above in reference to equation (6)), with less undesirable heating of the array, than in video image projectors known in the art.

In alternative preferred embodiments of the present invention (not shown in the figures), the desired phase shift at each element in the addressable array is determined in advance for each of a plurality of video images. Phase shift data thus determined are stored in digital form in digital storage media, or alternatively are converted to and stored in analog form, for example on tape, according to methods known in the art. The stored data are then input to driver circuitry, which drives the array accordingly, so as to create video images as described above.

In other preferred embodiments of the present invention, in which the incident beam comprises white or other polychromatic light, a mosaic color filter 56, as shown in Fig. 5, of a type known in the art, is introduced adjacent to array 40, or elsewhere in the optical system. The letters R, G, and B on mosaic elements 58 or filter 56 indicate the corresponding colors of the elements, red, green and blue respectively. Filter 56 filters light transmitted through array 40, so that the image then projected onto screen 50 is a color video image. Array 40 is driven by processor 42 so as to produce, at each element of the array, the desired phase shift for the wavelength of light transmitted by the corresponding element 58 of filter 56.

In preferred embodiments of the present invention in which the incident beam may comprise white or other polychromatic light, objective lens 44 and projection lens 48 are achromatic, compound lenses, of types known in the art. Fourier filter 46 is

preferably designed and fabricated, for example by multilayer dielectric coating, using alternating layers of positively- and negatively-dispersive materials, as is known in the art, so as to cause substantially equal phase shifts at all wavelengths of incident, visible light. In this case, the beam of light incident on array 40 may comprise polychromatic or white light, and the video image on screen 50 will be clearly focused for all colors in the incident beam.

As illustrated in Fig. 6, in another preferred embodiment of the present invention, color video projection apparatus comprises three video projectors 60, 62 and 64. Each of projectors 60, 62 and 64 is preferably substantially similar to apparatus 39, as shown in Fig. 4, including an addressable array of phase-shifting elements in each of the projectors. Projectors 60, 62 and 64 are illuminated by beams of a suitable color, preferably red, green and blue, respectively. The projectors are commonly driven by video driver 66, which preferably includes one or more processors, similar to processor 42, described in reference to Fig. 4. Video images thus produced in each of the three colors are commonly projected, as is known in the art, onto screen 50 to form a single color video image. Preferably the respective images projected by projectors 60, 62 and 64 are mutually shifted, so as to compensate for spatial offset between the projectors and form a color video image on screen 50 that is suitably registered.

Although the above preferred embodiments are described with reference to spatially-coherent incident beams, the principles of the present invention may also be applied to non-coherent incident beams having known spatial distribution. In general, Fourier filter 24 as defined by equation (3) will need to be replaced by a Fourier filter having different characteristics, depending on the spatial distribution of the incident beam. For example, if the source of the incident beam has an annular shape, then the phase retardation function of the Fourier filter should preferably have a matching annular profile, as described by Miles V. Klein and Thomas E. Furtrak, in <u>Optics</u> (Second Edition, John Wiley and Sons, New York, 1986), pages 486-487, and incorporated herein by reference. Other types of optical systems and Fourier filters incorporated in such systems may similarly be described, depending generally on the distribution of radiation incident on a phase element in the optical system.

It will be appreciated that although the above preferred embodiments have been described with reference to optical systems, the inventive principles of the present invention may similarly be applied to generate desired intensity distributions in beams of other types of radiation. For example, phase elements and Fourier filters may be designed and fabricated for use in shaping beams of microwaves, so as to project intensity distributions useful in radar systems. Beams of ultrasound radiation may be

projected and aimed at a target in a similar fashion, for use in ultrasound imaging and position detection systems, for example.

It will further be appreciated that the preferred embodiments described above are cited by way of example, and the full scope of the invention is limited only by the claims.

CLAIMS

1. A method for modulating a beam of radiation to project a desired intensity distribution, comprising:

selectively shifting the phase of the beam as a function of lateral position, based on the desired intensity distribution;

filtering the phase-shifted beam according to spatial frequencies thereof; and

focusing the filtered beam.

2. A method in accordance with claim 1, wherein selectively shifting the phase of the beam comprises determining a desired phase shift at a plurality of lateral positions in the beam, as a function of the desired intensity at respective, corresponding points in an image plane of the beam.

3. A method in accordance with claim 2, wherein selectively shifting the phase of the beam comprises generating driver signals, for driving an addressable array of phase-shifting elements to produce phase shifts in the beam.

4. A method in accordance with claim 3, wherein determining a desired phase shift comprises repeatedly changing the phase shifts of the phase-shifting elements, so as to project video images.

5. A method in accordance with any of the preceding claims, wherein filtering the beam comprises focusing the beam and shifting the phase of radiation in a central zone of the focused beam, relative to a constant phase shift applied to the remaining portion of the beam.

6. A method in accordance with claim 5, wherein shifting the phase of radiation in a central zone comprises shifting the phase by a phase shift generally equal to $\pi/3$ radians.

7. A method in accordance with any of the preceding claims, wherein modulating a beam of radiation comprises modulating a beam of coherent radiation.

8. A method in accordance with any of the preceding claims, wherein modulating a beam of radiation comprises a spatially uniform beam of radiation.

9. A method in accordance with any of claims 1-7, wherein modulating a beam of radiation comprises modulating a non-uniform beam of radiation.

10. A method for producing a phase element, for generating a desired intensity distribution, comprising:

determining a desired phase shift at a plurality of points in the phase element, as a function of the desired intensity at respective, corresponding points in an image plane; and

producing the desired phase shift at each of the plurality of positions.

11. A method in accordance with claim 10, wherein producing the desired phase shift comprises performing a multistep lithographic process.

12. A method in accordance with any of claims 2-7, wherein determining a desired phase shift comprises calculating a trigonometric function of the desired intensity.

13. A method in accordance with claims 10 and 11, wherein determining a desired phase shift comprises calculating a trigonometric function of the desired intensity.

14. A method in accordance with claim 12, wherein the trigonometric function is an inverse sine function.

15. A method in accordance with claim 13, wherein the trigonometric function is an inverse sine function.

16. A method in accordance with claim 14, wherein the inverse sine function is generally given by

$$\phi(x,y) = \sin^{-1}\{I'(x',y') - 1\}$$

wherein $\phi(x,y)$ is the desired phase shift, $I'(x',y')$ is the desired intensity distribution, and C is a constant.

17. A method in accordance with claim 15, wherein the inverse sine function is generally given by

$$\phi(x,y) = \sin^{-1}\{I'(x',y') - 1\}$$

wherein $\phi(x,y)$ is the desired phase shift, $I'(x',y')$ is the desired intensity distribution, and C is a constant.

18. Apparatus for generating an intensity distribution in a beam of light, comprising:

at least one optical phase element, on which a beam of light is incident, said element inducing laterally-varying phase shifts in the beam of light;

a Fourier filter, which receives light from the optical phase element and filters said light as a function of spatial frequency; and

an imaging lens, which receives light from the filter and focuses said light,

wherein the phase shift induced by each point in the optical phase element is determined by a desired intensity at a corresponding point in an image plane.

19. Apparatus in accordance with claim 18, wherein the optical phase element is a transmissive element.

20. Apparatus in accordance with claim 19, wherein the optical phase element is substantially transparent.

21. Apparatus in accordance with claim 20, wherein the optical phase element is a reflective element.

22. Apparatus in accordance with any of claims 18-21, and comprising an objective lens, which focuses light from the optical phase element onto the Fourier filter.

23. Apparatus in accordance with claim 22, wherein the Fourier filter comprises a central zone and a peripheral zone, wherein the central zone shifts the phase of light incident thereon relative to the phase of light incident on the peripheral zone, which shifts the phase of light incident thereon by a constant phase shift.

24. Apparatus in accordance with claim 23, wherein the peripheral zone comprises substantially all the area of the filter outside the central zone.

25. Apparatus in accordance with any of claims 18-21, wherein the optical phase element comprises a diffractive optical element.

26. Apparatus in accordance with any of claims 18-21, wherein the optical phase element comprises an addressable array of selectively-variable phase-shifting elements.

27. Apparatus in accordance with claim 26, wherein the addressable array comprises a liquid crystal matrix array.

28. Apparatus in accordance with claim 26 or 27, and comprising a mosaic color filter.

29. Apparatus in accordance with claim 28, wherein the mosaic color filter is adjacent to the addressable array.

30. Apparatus in accordance with any of claims 18-21, wherein the at least one optical phase element comprises three optical phase elements, arranged so that a beam of light of a different, respective color is incident on each of the optical phase elements, and the beams from the three optical phase elements are combined to form a color image.

31. Apparatus in accordance with any of claims 18-21 wherein, the apparatus is characterized by an optical magnification, and

wherein the beam of light incident on the at least one optical phase element has substantially uniform intensity, and

wherein the product of the intensity of light at a point in the image plane and the optical magnification is substantially greater than the intensity of the incident beam of light.

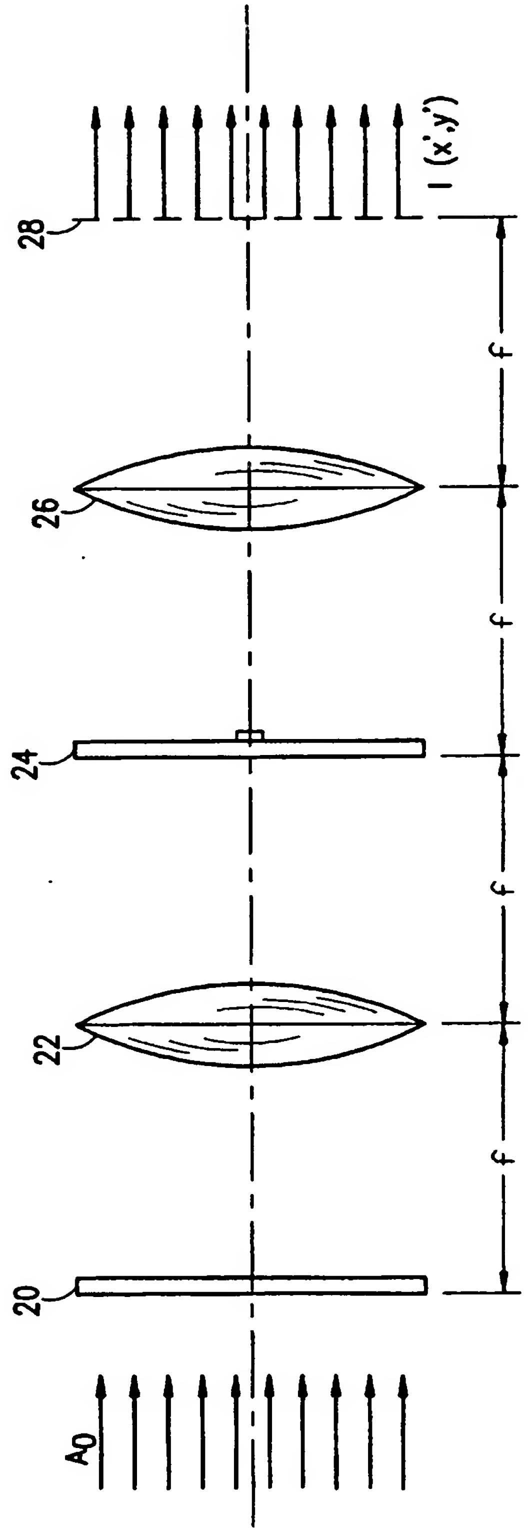


FIG. 1

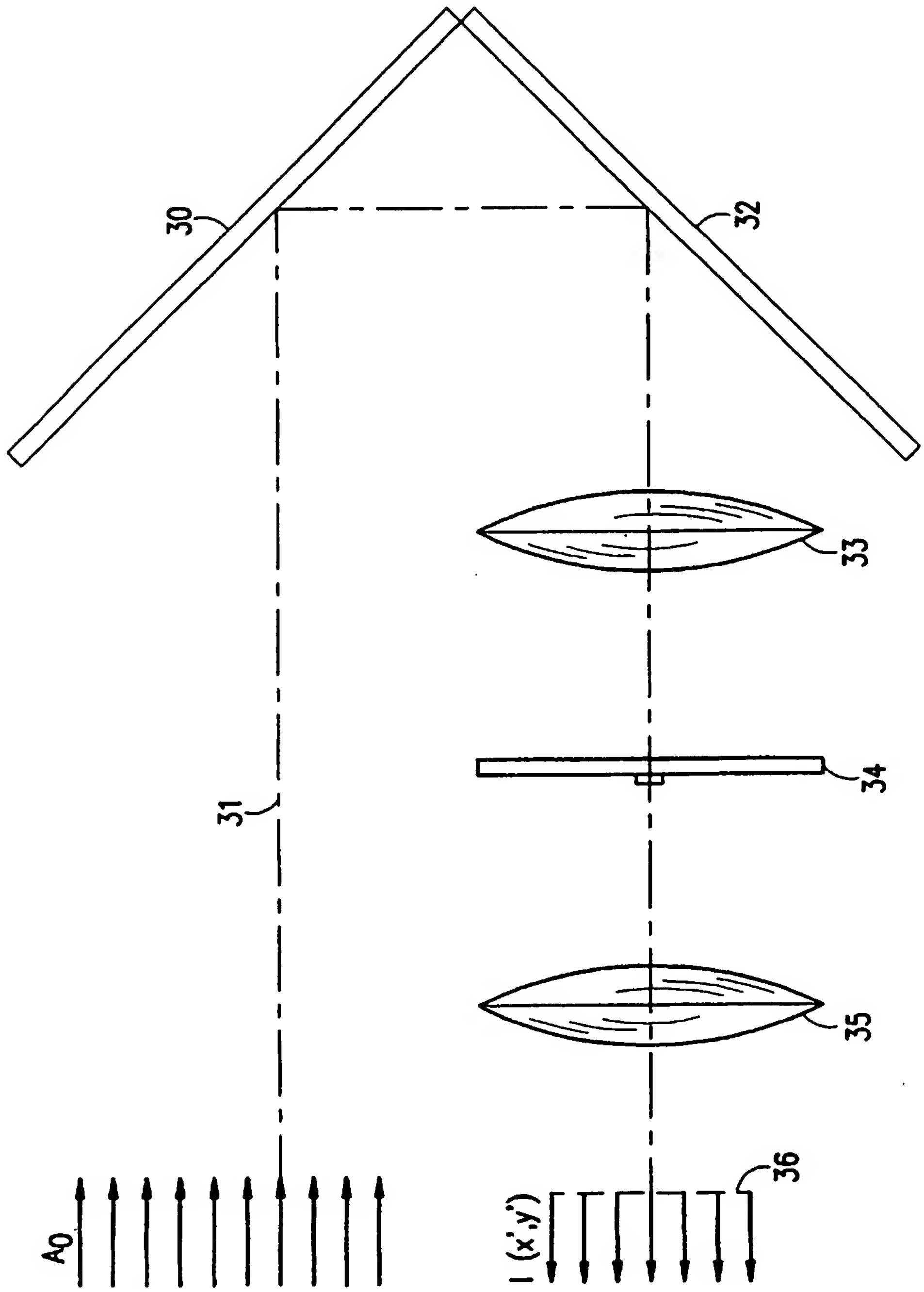


FIG. 2

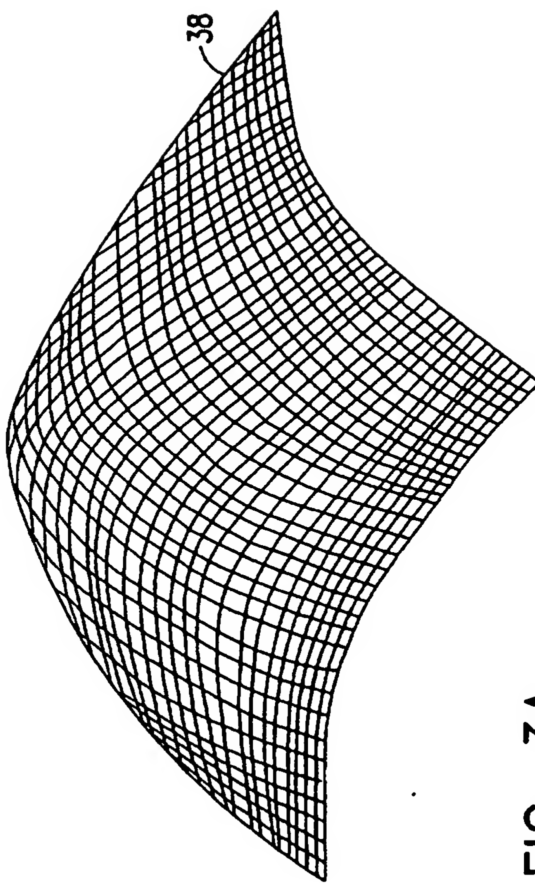


FIG. 3A

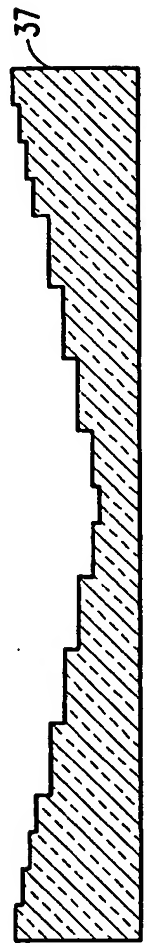


FIG. 3B

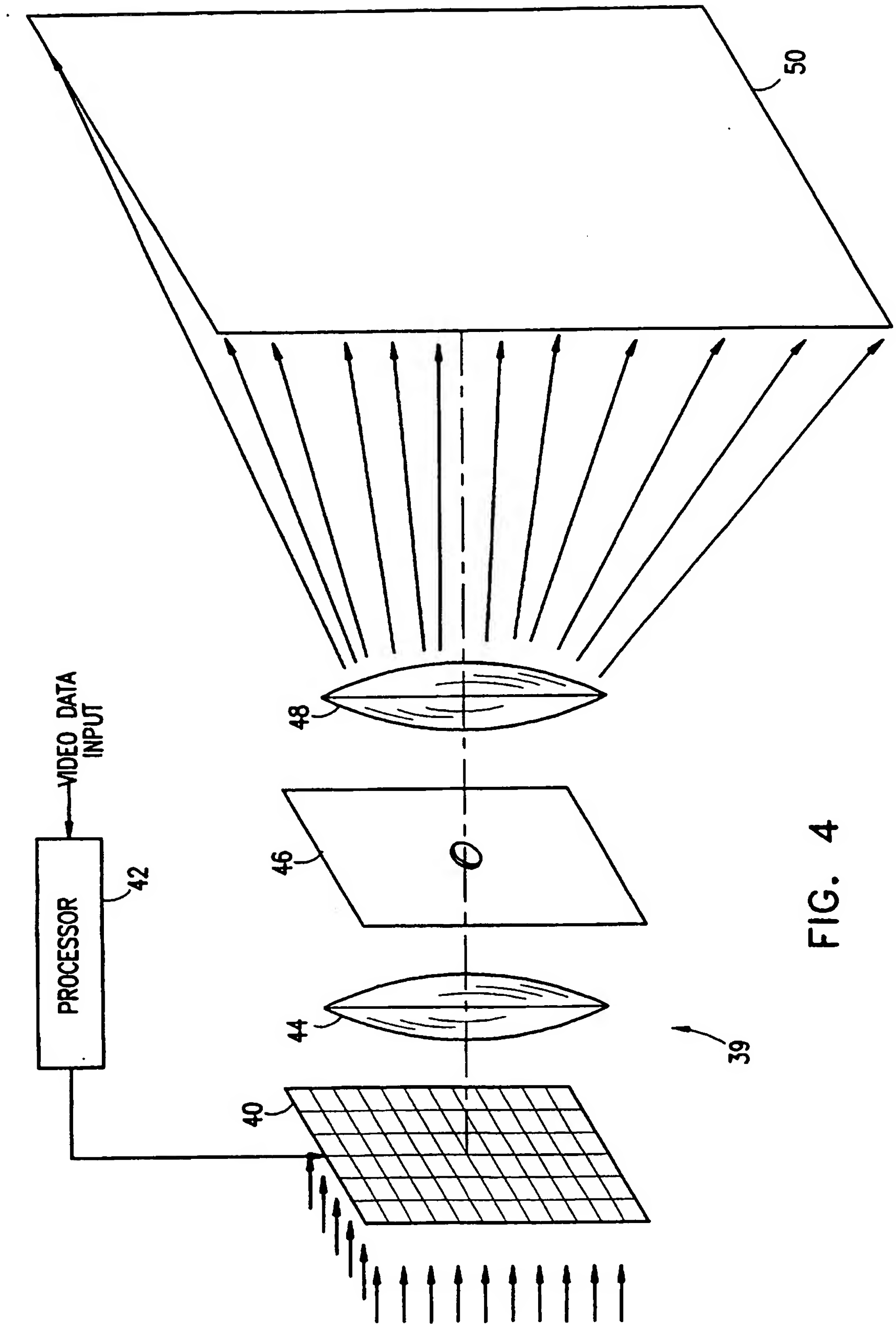


FIG. 4

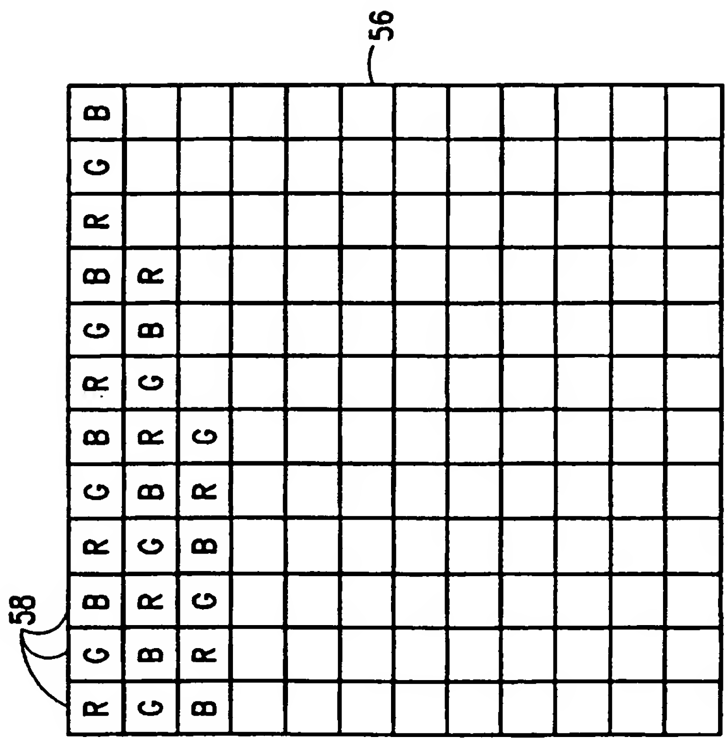


FIG. 5

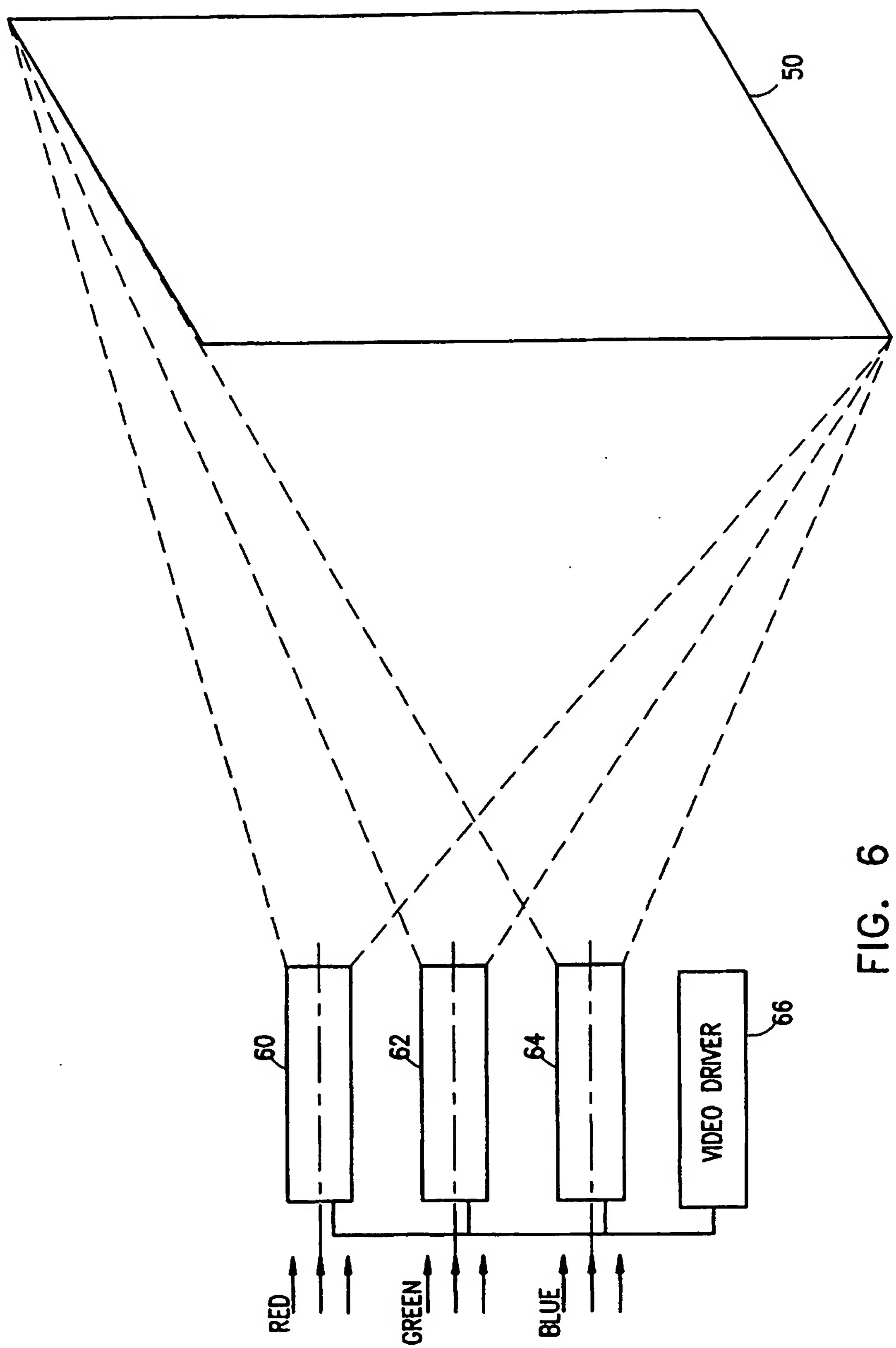


FIG. 6

INTERNATIONAL SEARCH REPORT	International application No. PCT/IL97/00136

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :GO2B 27/46
US CL :359/559
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/559, 263, 558, 563, 565, 566, 254, 315; 250/201.9; 356/121, 376

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

s phase and shift? and Fourier and filter and focus and spatial and frequency and central and uniform and modulat? and function

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,037,918 A (KATO) 26 July 1977 (26/07/77), cols. 3-6(all).	1-31
A	US 4,013,338 A (SATO ET AL) 22 March 1977 (22/03/77), cols. 3-6(all).	1-31
A	US 4,471,445 A (PERNICK) 11 September 1984 (11/09/84), cols. 3-8(all).	1-31
A	US 4,360,269 A (IWAMOTO ET AL) 23 November 1982 (23/11/82), cols. 3-7(all).	1-31
A	US 4,927,220 A (HESSELINK ET AL) 22 May 1990 (22/05/90), cols. 9-13(all).	1-31
A	US 5,046,827 A (FROST ET AL) 10 September 1991 (10/09/91), cols. 5-10(all).	1-31

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
03 SEPTEMBER 1997	24 SEP 1997
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer LOHA BEN Telephone No. (703) 308-4820

Form PCT/ISA/210 (second sheet)(July 1992)*

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL97/00136

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,142,413 A (KELLY) 25 August 1992 (25/08/92), cols. 2 and 3 (all).	1, 10, 18
A	US 5,189,548 A (HECHT) 23 February 1993 (23/02/93), cols. 2-9(all).	1-31
A	US 5,191,464 A (HECHT) 02 March 1993 (02/03/93), cols. 2-9(all).	1-31
A	US 5,218,469 A (HECHT) 08 June 1993 (08/06/93), cols. 3-9(all).	1-31